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ORIGINAL ARTICLE

Beneficiation of Saudi phosphate ores by column flotation technology

Tariq F. Al-Fariss, Farag A. Abd El-Aleem, Khaled A. El-Nagdy *

Phosphate and Mineral Processing Chair, Chemical Engineering Department, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

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Abstract Phosphoric acid industry is expected to develop in Saudi Arabia in the near future. This is ascribed to the discovery of phosphate in AI-Jalamid area located in the northern region of Saudi Arabia, the availability of sulfur as a by-product from petrochemical industries and the construction of phosphate fertilizers required by the growing agricultural sector. The discovered Saudi phosphate ores are of sedimentary origin with calcite and dolomite as the main impurities. The beneficiation of this type of ores is a key factor for the successful production of phosphoric acid by the wet process. In the present work, a flotation column has been designed and applied in the beneficiation of Al-Jalamid Saudi phosphate ores of the calcareous type by reverse scheme. The significant parameters like superficial gas velocity, slurry feed rate, particle size of processed ore, wash water consumption and collector dosage of flotation process are investigated to achieve the best recovery and quality of the beneficiated ores.

The results of this study revealed that column flotation technology is a promising tool for beneficiation of calcareous phosphate ores. A high purity ore of 35% P_2O_5 can be easily achieved at a high recovery value of 95% starting from a rock contains 25% P_2O_5, high calcite content (52.7% CaO) and $CaO:P_2O_5$ ratio equals 2.1.

1. Introduction

The development of column flotation is one of the most significant achievements in the mineral processing area. In fact, these column flotation units have a wide range of uses due to many factors like high selectivity of separation, simple processing control, low-energy consumption, absence of moving parts, low floor space requirements and simple design (Rubinstein, 1995; El-Shall et al., 2001). Moreover, the high efficiency of column flotation allows a reduction in the process time, a decrease in the number of stages and in the volume of the circulating load in the flotation circuit and as a result of this, an increase in the consistence and reliability of operations are expected. Due to all these advantages, column flotation is applied in the present work for beneficiation of Saudi phosphate ores.

Al-Jalamid area is one of the promising phosphate deposits in Saudi Arabia. The physical analysis carried out on this ore

* Corresponding author. Tel.: +966 555085099; fax: +966 1 4675486.
E-mail address: kelnagdy@hotmail.com (K.A. El-Nagdy).

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revealed that the mineralogical composition is mainly flouro-apatite and calcite with small quartz content. The presence of higher calcite content about 57.5% is a problem not only in Saudi phosphate ores but also for calcareous phosphate ores all over the world (Elgillani and Abouzeid, 2009; El-Shall, 1994; El-Shall et al., 1996).

The chemical analysis of the rock revealed that P_2O_5 = 25.1%, CaO = 52.7%, SiO_2 = 1.17% and CaO:P_2O_5 ratio = 2.1. The main problem of this ore is its high content of calcite mineral. The separation of such calcite gangue from apatite "phosphate mineral" is the main target of this beneficiation process. Hence, column flotation technology is investigated in the present work to account for its feasibility in this field. For this purpose, a column flotation unit was designed and the main significant factors affecting its performance were investigated.

2. Experimental

The experimental set-up used in the present work is shown schematically in Fig. 1. It consists mainly of the designed flotation column which is made of Perspex with 1.5 m height and 6.5 cm diameter. The column has a collection zone of 1.0 m and a cleaning zone of 30 cm. The column is also fitted with a mixing tank for the preparation and conditioning of slurry feed. Air enters the column at the bottom through its sparger which is a porous stainless steel mesh with 50 μm pores. The air line is fitted also with a pressure regulator and a flow meter. The slurry feed is introduced to the upper part of the column via its feed pump and below the wash water inlet which is located at 5 cm from the top. The froth phase is collected at the top of the column while the tailings are collected at the bottom. It is worth mentioning that the slurry feed distributor and wash water distributor are made from Plexiglass plates with 1.0 mm hole openings.

The slurry feed used in each experimental run was prepared from the crushed phosphate rock "of known particle size and P_2O_5 content" and tap water according to the solid content required. Then, the flotation reagents were added "oleic acid in kerosene as collector and frother, respectively (kerosene percentage is equal to 2.5 times the volume of the collector), Na_2SO_4 as depressor" to the slurry mixture and its pH was adjusted as required by the flotation process by using sodium hydroxide and sulfuric acid (Abdulrazik, 1990). After adjusting the feed mixture according to the required conditions, the experimental run was started by operating the feed pump, the wash water pump and the air valve at the required flow rates. Then allow the column to operate for a certain period until the flow pattern became stable and the column reaches its steady state operation. After that, the actual flow rates were measured and the discharged forth phase and tailings were sampled. The collected samples from these runs were dried, weighed and analyzed for P_2O_5 content. These analyses were carried out spectrophotometry using unicam spectrophotometer "Model SP8-400" at a wavelength of 420 nm. It is worth mentioning that the parameters investigated in the present work are: superficial gas velocity, particle size of phosphate ore, wash water rate, collector dose, slurry feed rate at the constant values of flotation parameters as shown in Table 1.

3. Results and discussions

The effect of superficial gas velocity, wash water rates, slurry flow rate, collector quantity, and particle size of phosphate ore on the flotation process has been studied. For this purpose, while studying the effect of any of the previous parameters on the flotation process, other parameters are kept constant at their desired levels as pH = 6.0–6.5, particle size = −250 +180 μm, pulp density = 10%, flotation time = 5 min, collector quantity = 1.82 kg/ton, depressor quantity = 2.0 kg/ton, wash water flow rate = 200 cm^3/min, slurry flow rate = 950 cm^3/min.

3.1. Effect of superficial gas velocity

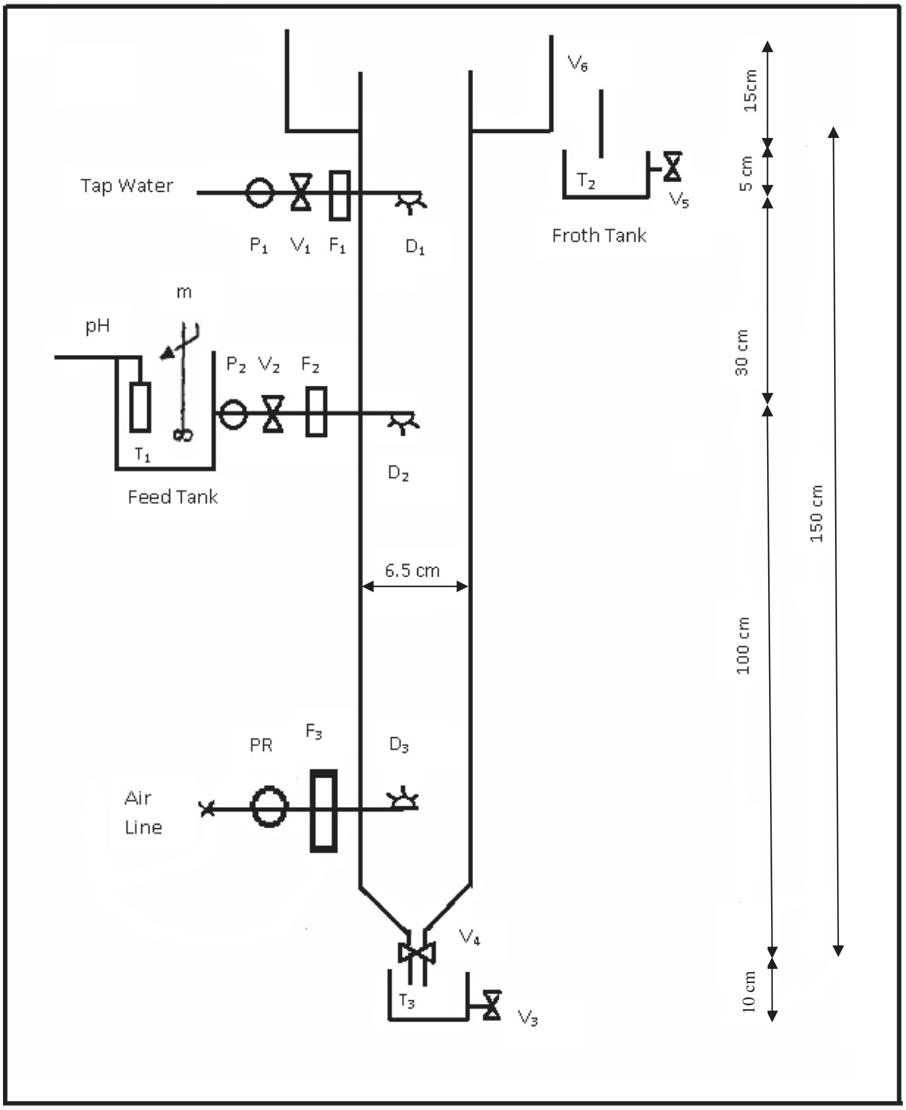
It is known that aeration determines the separation performance to a great extent in the flotation columns. It also affects the gas hold-up, the bubble size and the flow pattern inside the column. For this purpose, four superficial gas velocities are tested in our work (i.e., 3.5, 4.2, 4.9, and 5.6 cm/s). The result obtained is plotted in Fig. 2.

As shown in this figure, increasing the superficial gas velocity (at first from 3.5 to 4.9 cm/s) increases the P_2O_5 recovery as expected due to the increase in the gas hold-up and also due to the increase in bubbles attached with the solid particles as well as the increase in the bubble–particle collision. This improvement in recovery continues until a value 4.9 cm/s for air rate, beyond which the recovery decreases due to the coalescence of gas bubbles formed leading to the formation of large bubbles which lower the efficiency of flotation. Moreover, the capture efficiency between bubbles and solid particles is reduced at high flow rates resulting in lower P_2O_5 recovery. Fig. 2 also indicates an optimum value for recovery (91.1%) at superficial gas velocity 4.9 cm/s. Concerning the P_2O_5 content, it also has an optimum value of 29.0% at the same optimum air rate. This optimum value for superficial gas velocity in the flotation column was also observed by other workers in the literature (Rubinstein, 1995; Al-Fariss et al., 1993). This optimum value (4.9 cm/s) will be used in the next flotation runs.

3.2. Effect of wash water rate

Wash water is usually introduced at the top of the flotation column below the froth phase overflow. It is used for washing out the entrained fine particles in the froth phase. Hence, it can help in producing cleaner products and can also affect the column performance and stability. In the present work, wash water was introduced at 5 cm below the froth exit and its flow rate changed from 150 to 400 cm^3/min. Four experimental runs were carried out with this parameter while the other parameters were kept constant at the desired levels.

The collected samples from these runs were dried, weighed and analyzed for P_2O_5 content and recovery calculations as usual as shown in Fig. 3. The smaller value of wash water (150 cm^3/min) gives the best recovery (94.73%) and the best P_2O_5 content (35.2%). Therefore, the increase of wash water rate has negative effect on both recovery and purity which can be ascribed to the destruction of the froth layer formed inside the column. Moreover, the increase in wash water can also enhance the detachment of solid particles from the air bubbles resulting in less recovery. Henceforth, small wash water rates



T1	Mixing tank	D3	Air distributor
T2	Froth tank	V1-6	Valve
T3	Tailing tank	PR	Pressure regulator
F1	Water flow meter	m	Mixer
F2	Slurry flow meter	P1	Wash water pump
F3	Air flow meter	P2	Feed pump
D1	Distributor for liquid	pH	pH meter
D2	Distributor for liquid with wide holes		

Figure 1 The experimental set-up.

Table 1 Values of flotation parameters.

pH	6.0–6.5
Particle size	−250 +180 μm
Pulp density	10%
Flotation time	5 min
Collector dosage	1.82 kg/ton
Depressor dosage	2.0 kg/ton
Wash water flow rate	200 cm^3/min
Slurry flow rate	950 cm^3/min
Superficial gas velocity	4.9 cm/s

are preferable. Other workers in this field observed also similar trends for wash water during the application of column flotation for siliceous phosphate rocks (Von Holt and Franzidis, 1994; Abdel-Zaher, 2008). They reported also that wash water rates of about 13% of the slurry feed rate is preferred for phosphate flotation. Meanwhile, the best results are achieved at 150 cm^3/min, i.e., about 15.7% of the used slurry feed rate (950 cm^3/min).

3.3. *Effect of slurry flow rate*

The feed throughput ‘‘or the slurry flow rate’’ is a major operating parameter for any column flotation equipment. In order

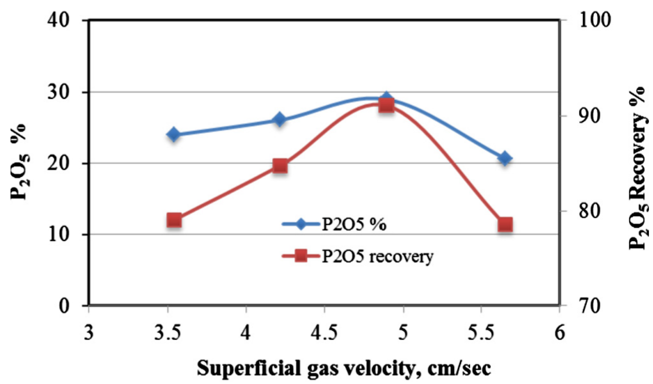


Figure 2 Effect of superficial gas velocity.

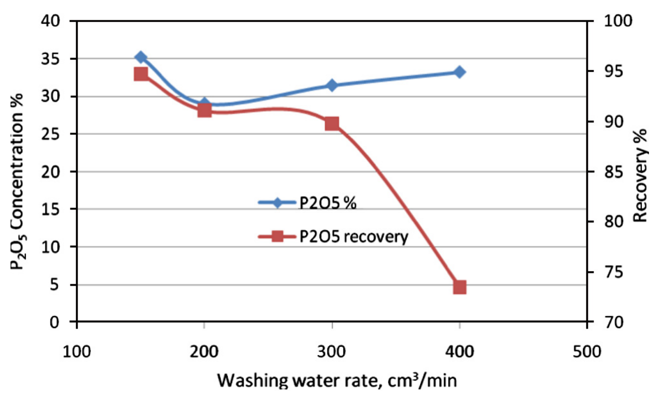


Figure 3 Effect of wash water flow rate.

to elucidate the effect of this parameter, its value was varied from 956 to 2630 cm^3/min, at four levels while keeping the other parameters constant.

As shown in Fig. 4, both P_2O_5 recovery and P_2O_5 content decrease by increasing the slurry flow rate from 956 to 2023 cm^3/min. This decrease in recovery and grade can be ascribed to the decrease in retention time of slurry inside the column.

This reduction in the solids retention time means less flotation time inside the column and hence less recovery and less grade as expected. But, at slurry rate higher than 2023 ml/min, both recovery and grade are improved as shown in Fig. 4. This improvement can be ascribed to the positive effect of slurry rate on the rise velocity of bubbles as recommended by other workers (Rubinstein, 1995; El-Shall et al., 2001). They reported that increasing of slurry rate after some extent can reduce the bubble rise velocity and hence increasing the bubble retention times and in turn increasing the bubble loading (or increase the gas hold-up inside the column) resulting in improving both recovery and grade as shown in Fig. 4. However, the best results achieved are at a smaller slurry rate where the highest recovery (94.7%) and the best grade (35.2% P_2O_5) are obtained at the smallest slurry rate (956 cm^3/min).

3.4. Effect of collector dosage

The collector used in the present work is oleic acid dissolved in kerosene (kerosene:oleic acid is 2.5:1), as it revealed promising results with phosphate beneficiation (Abdulrazik, 1990; Al-Fariss et al., 2011). For better understanding of the collector effect on the performance of column flotation, various collector dosages are investigated. Four levels of collector dosages were used "1.82, 2, 3, 4 kg/tons" together with suitable amounts of kerosene. As shown in Fig. 5, a small increase in P_2O_5 recovery (from 94.73% to 95.91%) is observed with increasing the collector dosage from 1.82 to 4.0 kg/ton which can be ascribed to the improvement in the hydrophobicity of floating particles. However, the P_2O_5 content of the product decreases from 35.2% to 31.13% at first within a collector range of 1.82–2.0 kg/ton, then starts to increase again until it reaches a value of 34.62% P_2O_5 at a collector dosage of 4 kg/ton. The initial decrease in P_2O_5 content can be ascribed to the improved hydrophobicity of both calcite and apatite present in the phosphate rock enhancing the flotation of both minerals and in turn less P_2O_5 content in the final product. But with increasing the collector dosage (> 2 kg/ton) the selectivity for calcite separation increases giving more P_2O_5 purity in the final product.

The lower value of the collector dosage (1.82 kg/ton) is the best level at which both recovery and grade reach their best values (94.73% for recovery and 35.2% P_2O_5 content). Hence the 1.82 kg/ton collector is selected as an optimum dosage.

3.5. Effect of particle size of phosphate ores

Three levels of particle size [(−180 +125 μm), (−250 +180 μm) and (−425 +250 μm)] were prepared as separate size fractions keeping the other parameters constant. The relation between the average size (150, 215 and 335 μm) and the P_2O_5% and its recovery is plotted as shown in Fig. 6. The results showed that the optimum recovery (94.73%) was

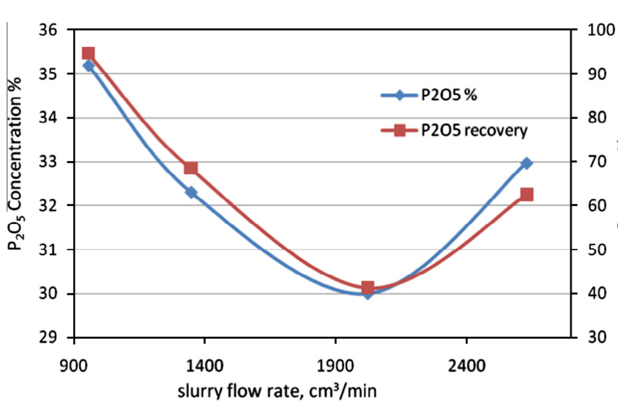


Figure 4 Effect of slurry flow rate.

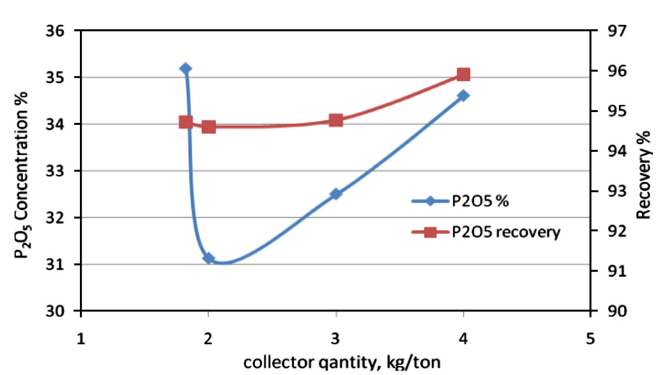


Figure 5 Effect of collector quantity.

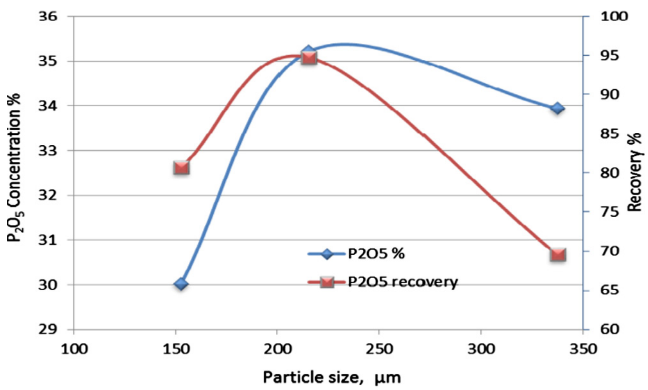


Figure 6 Effect of particle size.

achieved at a particle size of −250 +180 µm. The P_2O_5 content of this size has also an optimum P_2O_5 content (35.2%).

It can be stated that larger particles than this optimum size decreases both recovery and grade due to their lower retention time inside the column. On the other hand, fine particles (smaller than −250 +180 µm) have weak attachment to the surface of the bubble phase in the collection zone and may be carried out easily with the streams of wash water used. Special designs of the column flotation units are required to handle either ultra fine or coarse particles (Elgillani and Abouzeid, 2009; Guo and Li, 2010). Coarse particles can also be floated in column flotation under negative bias (El-Shall et al., 1988, 2000, 2001, 2003, 2004).

4. Conclusions

The experimental results obtained in this study led to the following conclusions:

1. It is possible to beneficiate the AI-Jalamid phosphate rock by column flotation to obtain a concentrated product enough for wet process phosphoric acid production.
2. This flotation technology gives good beneficiation results, i.e. P_2O_5 concentration above 35%, recovery above 95% and a lower $CaO:P_2O_5$ ratio of 1.53 from a feed containing 25% P_2O_5 and $CaO:P_2O_5$ 2.1.
3. Results showed that the lowest wash water (150 cm^3/min) is enough to purify the froth, but high wash water rate is not recommended due to loss in P_2O_5 recovery.
4. The slurry flow rate has to be kept at its lowest level (956 cm^3/min) to increase its retention time and in turn improving recovery and purity of products.
5. The optimum conditions achieved in this work are: superficial gas velocity = 4.9 cm/s, wash water flow rate = 150 ml/min, slurry flow rate = 956 ml/min, depressor quantity = 2.0 kg/ton, collector quantity = 1.82 kg/ton and particle size = −250 +180 µm.

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